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USE OF CAESIUM-137 RE-SAMPLING AND EXCESS LEAD-210 TECHNIQUES TO ASSESS CHANGES IN SOIL REDISTRIBUTION RATES WITHIN AN AGRICULTURAL FIELD IN NAKHLA WATERSHED

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Abstract

The Nakhla watershed was one of the most affected areas by water erosion in Northwest Morocco. This phenomenon caused the sedimentation of the Nakhla dam, an important water reservoir that contributed to water supply in the region. The motivation behind our investigation is to know the evolution of the situation in this watershed. The objective of this study is to use fallout Caesium-137 and excess Lead-210 to assess changes in soil redistribution rates during the last century and the impact of recent soil conservation practices within an agricultural field in the Nakhla watershed. The Caesium-137 technique, which has proved its efficiency in estimating erosion rates over the last 50-60 years, was associated with the re-sampling approach in the current study to reveal the response of soil redistribution rates to land use change over the last fifteen years within an upland agricultural field in Northwest Morocco under Mediterranean conditions. The excess Lead-210 was used to generate data on soil movement over a longer time window of 100 years. Subsequently, the combined use of Caesium-137 re-sampling with excess Lead-210 techniques allowed for the estimation of soil erosion rates over three periods: 1954-2002, 1954-2017 and 1917-2017. Quantification of water erosion with excess Lead-210 indicated a rate of 27 t ha^{-1} yr^{-1}. Based on Caesium-137 measurements, the comparative analysis of the soil redistribution estimates over two periods (1954-2002 and 1954-2017) shows that soil loss rates have significantly decreased from 36 t ha^{-1} yr^{-1} to 29 t ha^{-1} yr^{-1} during the period between the two sampling campaigns (2002-2017) due to the beneficial impact of agricultural practices. This decrease is consistent with the available records of sediment yield in the Nakhla dam during these periods. The main findings show that the sustainable agricultural practices and the implemented soil erosion control strategy, based on more frequent fallow with natural vegetation and olive plantations, were effective in reducing soil erosion in the investigated area.

Keywords: Soil redistribution, Nakhla watershed, Caesium-137, excess Lead-210, re-sampling approach.

1. Introduction

Water erosion is seen as a serious agro-environmental threat in Northwest Morocco. It strongly affects soil properties and functions (El Well, 1984; Lal, 2003; Mabit et al., 1998) and causes the loss of soil which is not renewable at the human timescale. This affects the capability of soils to support the local needs of agriculture. Furthermore, not only does severe water erosion imply the soil loss induced by high run-off, but also low groundwater supplies in the region. The eroded particles are deposited in dams causing their siltation which exposes the region to water stress. Indeed, studies have shown that the highest rates of sedimentation in Morocco were recorded in water reservoirs located in the rifaine chain (Moukhchane, 2002). This damage creates a substantial financial loss for the Moroccan government and impacts the socio-economic development of this region. For instance, the storage capacity of the Nakhla dam, that had contributed to the water supply of Tetouan city since 1962, has progressively decreased due to the magnitude of the accelerated erosive risk, described by numerous studies in the watershed (Bouhlassa et al., 2000; Hassouni and Bouhlassa, 2006; Moukhchane, 2002). These investigations were carried out to establish a reliable database on soil loss and sediment budgets with the aim of promoting strategies for better soil and water management within the watershed, especially because climate change could further impact the situation in Mediterranean areas (Garcia-Ruiz et al., 2013). In Morocco, climate change has caused extreme weather events in the past few decades. They consist of more frequent and acute floods and long periods of droughts (Stour and Agoumi, 2008). In this regard, the government has devoted more attention to the fate of natural resources and to Nakhla watershed management, and thus launched a national program, in 1996, entitled, “Plan National d’Aménagement des Bassins Versants (PNABV)” (Haut Commissariat des Eaux et Forêts et la Lutte contre la Désertification, 2012) in addition to another program named, “Pérennité

des Ressources en Eaux du Maroc (PREM)" (Secrétariat d'Etat chargé de l'Environnement, 2004). These programs were established to mitigate the in-site and off-site effects of the phenomenon and to reduce soil losses for a sustainable management of water resources in the Nakhla watershed.

The "PREM" project confirmed that the problem must be defined within the socio-economic context of the population and their practices, then integrate their participation to select the suitable soil conservation strategies. This participatory approach raised the awareness of farmers about the importance of soil conservation strategies and was fundamental for the success of the project. The main objectives were to diagnose the erosive risk in the basin, to identify the constraints that affect the sustainability of natural resources in the area and to develop strategies for sustainable practices. The survey indicated that soil erosion resulted from the interaction of different factors related to the geomorphological and lithological characteristics of the area (high altitudes, high slopes and fragile soils), climatic factors (heavy rain and concentration of rainfall in short periods), cultivation on hillslopes, the expansion of crops on vulnerable lands, overgrazing and deforestation. It was reported that the cultivated lands contributed more than 30% to the sediment delivery at Nakhla watershed (Bouabid et al., 1996; Bouhlassa et al., 2000). Therefore, in order to control the erosive risk, the watershed was dealt within two parts with different land uses: annual croplands concentrated mainly in the upstream part where soil erosion is intense and a forested area in the downstream part where the erosion process is less severe. The nature of the geological substratum and the lack of a protective plant cover on the steep slopes of the upstream part make it the most susceptible to water erosion. In 1997, the direct interventions targeted in this area based on the plantation of olive trees in contour lines and then, the mechanical and biological stabilization of gullies (Service des Etudes des Aménagements des Forêts et des Bassins Versants de Tétouan, 2003, 2004). After discussions with local farmers, the project invested in the planting of almond and fig trees since they are species adapted to the climatic conditions of the region. About 130 trees per hectare were planted in the fields with a vertical spacing of 2 meters and a horizontal spacing of 7 meters. These distances were fixed based on the suggestions of farmers and took into account the issue of future intercropping. The Ministry of Agriculture, Fisheries, Rural Development, Water and Forests in collaboration with the Regional Direction of Water and Forests, was in charge of the implementation of these direct interventions, while the indirect interventions were performed by several partners including some non-governmental organizations (NGOs). The complementarity between the direct and indirect interventions guaranteed the reinforcement of soil conservation practices in the area.

Evaluation of the impact of watershed management on soil loss is needed so that reliable datasets on the magnitude of erosion and effectiveness of soil conservation practices, especially in upland areas where the impact of soil erosion is highly visible, as well as data on the change in soil redistribution rates can be established for decision makers.

Classical techniques such as empirical erosion models and experimental runoff plots were generally used to quantify water-induced soil erosion in the Rif Mountains. Nevertheless, the use of fallout radionuclides (FRNs) such as Caesium-137 (^{137}Cs) and excess Lead-210 (^{210}Pb$_{ex}$) is an excellent alternative for soil erosion studies in this region (Benmansour et al., 2002; Damnati et al., 2013; Sadiki et al., 2007) and has many advantages compared to the conventional methods (Matisoff and Whiting, 2011; Walling, 2012; Zupanc and Mabit, 2010). Indeed, ^{137}Cs and excess ^{210}Pb$_{ex}$ with half-lives of 30.2 and 22.3 years respectively allow for the estimation of mid-term and long term soil erosion rates extending over ca. 60 and 100 years respectively under different agro-environmental conditions from the plot to the watershed scale (Mabit et al., 2008). Due to its natural origin, the fallout input of ^{210}Pb$_{ex}$ is continuous in time, while ^{137}Cs is an anthropogenic isotope that was introduced into the environment by the nuclear bomb tests in the 1950s and 1960s and was subsequently added in 1986 by the Chernobyl incident. Fallout radionuclides are adsorbed onto the surface of aerosols and dust particles, and are then distributed across the landscape by wet and dry fallout. Once deposited at the surface of the soil, they are rapidly adsorbed on the fine soil particles and can serve as very effective soil tracers (Walling and He, 1997; Xinbao et al., 2003). The measurements of their inventories in soil provide information on loss and gain, compared with a stable site inventory that represents the initial stock of the radionuclides

in the area. The use of $^{210}Pb_{ex}$ allows for the removal of some drawbacks related to the low ^{137}Cs inventories sometimes observed in the southern hemisphere and the impact of Chernobyl incident in some areas, where additional fallout of ^{137}Cs inputs can complicate the interpretation of ^{137}Cs measurements (Bernard et al.,1998, Mabit et al.,2008). While $^{210}Pb_{ex}$ has been widely used since the 1970s for dating sediment deposits in a range of sedimentary environments, it is only since the mid-1990s that studies have used $^{210}Pb_{ex}$ for estimating soil redistribution rates (Mabit et al., 2014). The application of $^{210}Pb_{ex}$ at Nakhla watershed to assess soil erosion was restricted to only one study carried out by Ibrahimi, (2005), whereas ^{137}Cs was used several times (Hassouni and Bouhlassa, 2006; Ibrahimi, 2005; Moukhchane, 2002). These two fallout radionuclides have been recognized as reliable soil tracers and are further investigated in the current study to explore their potential in documenting changes in soil redistribution. In this regard, the study reported by Ibrahimi, (2005) within an agricultural field in Nakhla watershed provided the basis for deducing temporal changes in soil redistribution rates in the same study area, using the same fallout radionuclides. Indeed, the growing need for a scientific alternative that reflects the response of soil movements to land use has led to the association of nuclear techniques with the re-sampling approach. This combination constitutes one of the last advances in investigating temporal changes in soil redistribution rates (Porto et al., 2014, 2016). Therefore, the objectives of this work are to use ^{137}Cs re-sampling with excess ^{210}Pb techniques to document soil erosion and deposition rates over three periods (1954-2002, 1954-2017 and 1917-2017) and to assess the effectiveness of recent soil conservation practices in an agricultural field in Nakhla watershed.

2. Study area

The study site is an agricultural field located in the southwest of the Nakhla watershed (35°N 20', 5°W 22'), within the occidental part of the Rif Mountains, Northwest of Morocco (Fig. 1). On the east side of the field, the calcareous dorsal appears, while on the north side, sits the Nakhla dam with a storage capacity of 9 Mm^3. The study field is located in the upstream part of the watershed, at around 683 m high with a mean slope of about 30%. It was reported that the steep slopes which characterize lands in this area are the result of climatic, geological and biological factors that occurred during the Quaternary period, causing upstream erosion, transportation of the eroded material and its deposition downstream (Naïmi and Bouabid, 1997).

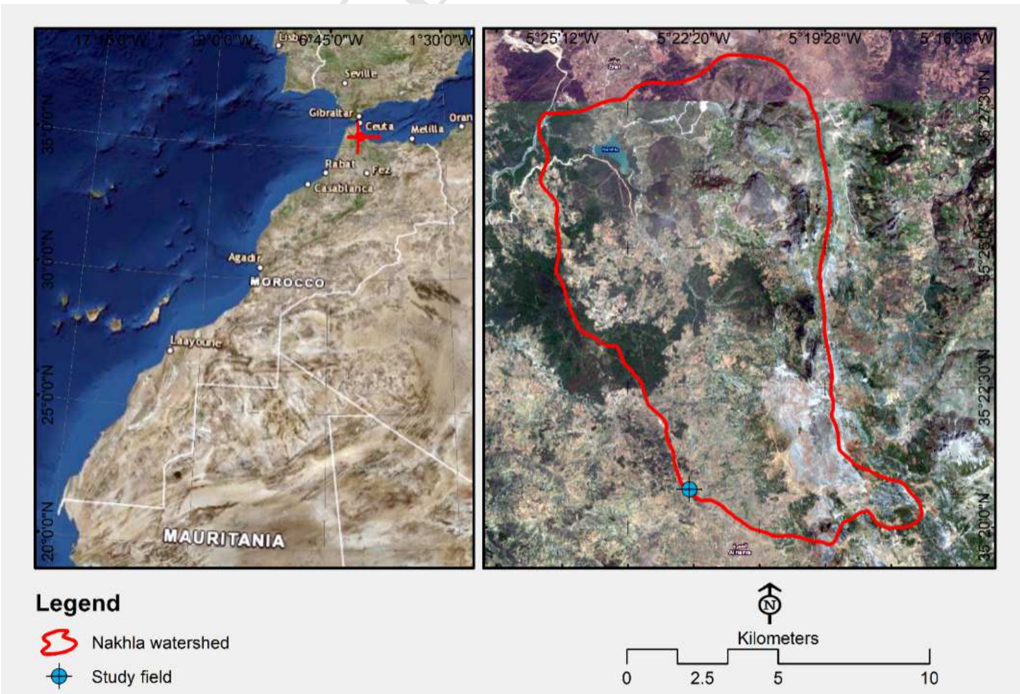

Fig.1.Location of the study area.

The field is subject to a Mediterranean climate which is characterized by a hot dry summer and a wet winter. The annual rainfalls, from 1979 to 2017, recorded by meteorological stations of the Nakhla watershed are reported in Fig. 2. The average annual precipitation from 1980 to 2017 was about 741 mm. The diagram shows that the two periods from 1995 to 1998 and from 2008 to 2011 recorded heavy rains with average values of 1216 and 1208 mm respectively (Fig. 2), whereas the minimum values of precipitation were obtained for the period 2004-2007 with an average value of 475 mm.

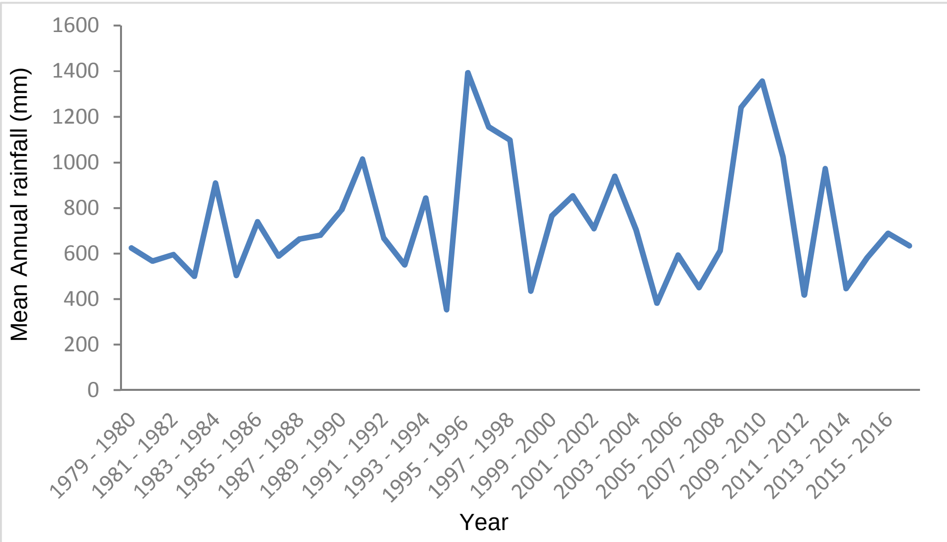

Fig 2. Diagram of mean annual rainfall in Nakhla watershed.

According to Damnati et al., (2010), the study field is dominated by clays and silts. This soil texture is considered the main constraint that limits water retention and consequently, favors soil erosion in the entire region (Naïmi and Bouabid, 1997). In addition, the field is characterized by a low average content of calcium carbonates ($CaCO_3$) that does not exceed 1% (Ibrahimi, 2005). The investigated agricultural field was generally cultivated in the past, before 2002, by cereals in rotation with legumes under conventional tillage. In the last fifteen years (2002-2017), a change has occurred in this field consisting of more frequent fallows combined with natural vegetation and olive trees.

3. Materials and methods

3.1. Re-sampling

The site that was sampled in 2002 and 2003 (Ibrahimi, 2005), based on a multiple transect strategy and ^{137}Cs and $^{210}Pb_{ex}$ measurements to quantify soil erosion on a small scale, was revisited in 2017 for re-sampling purposes. Consistently with the original sampling design (Damnati et al., 2010; Ibrahimi, 2005), twenty soil samples were collected from points laterally spaced by a distance of 1.5 m and by 5 m along four parallel transects, following the slope gradient and the run-off direction. A total of 20 samples were collected from the field including 19 bulk cores and one depth profile with 5 cm increment using a soil column cylinder auger of 9 cm in diameter and 90 cm in length driven into the ground by a motorized percussion corer to depths ranging between 28 and 42 cm. An additional sectioned core with a depth interval ranging between 3 and 4 cm, at 20 cm deep, was taken from the reference site, in the neighborhood of the investigated field, using the same sampling tool which is able to

counter the stony and compacted soil of the area. This sectioned core was collected to obtain the vertical distribution of both radioisotopes in order to ensure that the reference site had not been disturbed during the period between the two sampling campaigns. Moreover, in order to provide accurate estimations of the central tendency in the reference site, eight bulk cores were collected according to a systematic grid. The bulk cores were collected to measure the inventories of radionuclides whilst the incremental samples allowed to establish the depth profiles associated with reference and cultivated fields.

3.2. Laboratory analyses

Soil samples were first oven dried at 60°C for 72 hours, disaggregated and ground, then sieved at 2 mm and homogenized. Sub-samples from bulk and incremental samples respectively were later placed in cylindrical plastic pots of 200 ml and analyzed by a gamma spectrometric chain using a High Purity Germanium Coaxial Detector (HPGe), (broad energy detector, 50% efficiency) for ^{137}Cs, ^{210}Pb$_{tot}$ and ^{226}Ra (via ^{214}Bi) measurements. The activities of the radioisotopes, ^{137}Cs, ^{210}Pb and ^{214}Bi were determined from the net peak areas of gamma rays at 661.6, 46.5 and 609 KeV respectively. The detector was calibrated using certified multi-gamma sources and two IAEA reference materials (IAEA 327, Soil 1). ^{210}Pb needs particular attention for accurate measurements (Shakhashiro and Mabit, 2009). The measurement of ^{226}Ra, through its daughter ^{214}Bi, requires sealing soil samples for 21 days to stop the emanation of ^{222}Rn and achieve equilibrium between ^{226}Ra and ^{214}Bi. Then, the ^{210}Pb$_{ex}$ concentration was calculated by subtracting ^{214}Bi activity from total ^{210}Pb activity (^{210}Pb$_{tot}$). The self-absorption correction was performed according to a simple experimental approach (Benmansour et al., 2013; Cutshall et al., 1983; Khater and Ebaid, 2008) based on transmission measurements. The counting times were between 12 and 24 hours. Under these conditions, the detection limits were about 0.20-0.40 Bq kg^{-1} for ^{137}Cs, 2-4 Bq kg^{-1} for ^{210}Pb and 0.40-0.60 for ^{214}Bi. Relative uncertainties (2σ) on measurements associated with ^{137}Cs activities were generally found in the range of 6-12 %, but for few samples, with very low activities, the relative uncertainties could reach 40%. Regarding ^{210}Pb and ^{214}Bi activities, the uncertainties ranged between 10-15 % and 5-8 % respectively. However, due to the close value of the ^{214}Bi activity to total ^{210}Pb, relative uncertainties corresponding to ^{210}Pb$_{ex}$ for most bulk samples were high between 30-50%. Lower uncertainties of about 15-20 % were measured for higher activities of ^{210}Pb$_{ex}$ observed for the upper layers of the depth profiles.

The inventory (Bq m^{-2}) of each sample was calculated as the product of the measured ^{137}Cs or ^{210}Pb$_{ex}$ activity (Bq kg^{-1}) and the dry mass of the <2mm fraction (kg) of the corresponding sample, divided by the sectional area of the sampling device (m^2).

3.3. Erosion rates estimations

The ^{137}Cs and ^{210}Pb$_{ex}$ local areal activities (Bq m^{-2}) corresponding to each transect were converted into erosion rates (t ha^{-1} yr^{-1}) through the Mass Balance Model 2 (MBM2) (Walling et al., 2002). Indeed, the Mass Balance Model 2 (MBM2) is more realistic than other conversion models, namely Proportional Model (PM) and Mass Balance Model 1 (MBM1) since it takes into account both the temporal variation of the ^{137}Cs fallout input and the fate of the freshly deposited ^{137}Cs fallout prior to incorporation into the plough layer by tillage (Hassouni and Bouhlassa, 2006; Walling et al., 2002). MBM2 was used to derive erosion rates from the two ^{137}Cs datasets since the use of the same conversion model is required for comparison between the two periods. MBM2 can be expressed as follows:

$$\mathrm{d}(A)/\mathrm{d}t=(1-\Gamma)I(t)-(\lambda+PR/d)A(t) \quad (1)$$

where $A(t)$ is the ^{137}Cs ($^{210}Pb_{ex}$) inventories (Bq m^{-2}); t is the time since the onset of ^{137}Cs ($^{210}Pb_{ex}$) fallout (yr) considered in 1954; R is the soil erosion rate (kg m^{-2} yr^{-1}); d is the cumulative mass depth representing the average plough depth (kg m^{-2}); λ is the decay constant for ^{137}Cs ($^{210}Pb_{ex}$) (yr^{-1}); $I(t)$ is the annual deposition flux at time t (Bq m^{-2} yr^{-1}); Γ is the proportion of the recently deposited ^{137}Cs ($^{210}Pb_{ex}$) removed by erosion before being mixed into the plough layer, also called proportion factor; P is the particle size factor.

Except for the tillage depths associated with each sampling campaign, the other parameters were fixed for the two sets of calculations.

The estimation of soil distribution rates, based on $^{210}Pb_{ex}$, was not integrated into the re-sampling procedure. Therefore, the interpretation of the recent results was independant from those obtained in 2002. Since $^{210}Pb_{ex}$ provides retrospective estimates of 100 years before the sampling year, the assumptions of erosion rates were obtained from 1917 to 2017 (Table 1), whereas ^{137}Cs permitted to obtain the annual soil losses for the periods 1954-2002 and 1954-2017 (Table 1.).

Table 1. Calculation of erosion rates based on ^{137}Cs and $^{210}Pb_{ex}$

The employed radionuclide	Period	Number of years corresponding to the period (yr)	Erosion rate (t ha^{-1} yr^{-1})	Total amount of soil removed from the field (t ha^{-1})
$^{210}Pb_{ex}$	1917-2017	100	R1	100× R1
^{137}Cs	1954-2017	63	R2	63 × R2
^{137}Cs	1954-2002	48	R3	48 × R3

4. Results and discussion

4.1. Vertical distributions and inventories of ^{137}Cs and $^{210}Pb_{ex}$ in the reference site

The shapes of the ^{137}Cs and $^{210}Pb_{ex}$ depth profile taken from the reference site during the 2017 sampling campaign confirm that it had not been disturbed during the period between the two samplings (Fig. 3 A & B). Around 90% of ^{137}Cs and $^{210}Pb_{ex}$ are retained in the four upper layers (0-12 cm), then concentrations decrease with depth according to an exponential shape for both radionuclides. Similar behaviours were observed in other studies in Morocco (eg. Benmansour et al., 2013; Damnati et al., 2013). In the case of $^{210}Pb_{ex}$, the profile shows that the highest activity of about 90.9 ± 15.8 Bq kg^{-1} is found at the surface (0-3 cm) followed by a sharp decline of $^{210}Pb_{ex}$, due to the continuous input through time (Fig. 3 B), whereas the activity of ^{137}Cs declines slowly with depth starting from a concentration of 12.9 ± 0.8 (Fig. 3 A). This difference can be explained by the bioturbation process which produces a near-constant ^{137}Cs concentration in the upper 3-4 cm and also by the deposit of fallout of ^{137}Cs which has been substantially reduced after the sixties (Benmansour et al., 2013; Walling and Quine, 1995). This feature makes a morphological difference in the distribution profiles of the two radionuclides with depth (Fig. 3 A & B). The mean reference inventories of ^{137}Cs and $^{210}Pb_{ex}$ obtained in 2017 were estimated to be 1517 ± 223 Bq m^{-2} and 3662 ± 1404 Bq m^{-2} respectively. Taking into account the relation established between ^{137}Cs inventory and precipitation in different regions of Morocco (Benmansour, et al., 2013), the obtained value of ^{137}Cs seems to be consistent with previous data. Indeed, according to the obtained linear equation between ^{137}Cs inventory and precipitation, the predicted inventory in 2017 in this study area would have been about 1695 Bq m^{-2}. Regarding the use of $^{210}Pb_{ex}$, very few studies on soil erosion were performed in Morocco. However, we should mention that $^{210}Pb_{ex}$ reference inventory value obtained in 2017 in the Northwest region near Tetouan city is

slightly higher than the one found in a region located in the west, 70 km from Rabat city, with lower precipitation (Benmansour et al., 2011, 2013; Nouira et al., 2007).

Almost the same ^{137}Cs depth profile shape, like the one found in 2017, was obtained during the 2002 sampling campaign. Indeed, the ^{137}Cs activity sharply decreased with depth and around 96% of ^{137}Cs were retained in the upper 0-15 cm of the depth profile collected in 2002 (Fig.3 C). A minor difference in the shapes of the two depth profiles could be explained by the different depth increments used for each period (Fig 3 A & C). The mean reference inventory of ^{137}Cs obtained in 2002 was found to be about 2142 ± 254 Bq m^{-2} (Damnati et al., 2010, 2013). By radioactive decay correction up until 2017, this value becomes 1520 ± 180 Bq m^{-2} which is in agreement with the ^{137}Cs inventory determined in 2017.

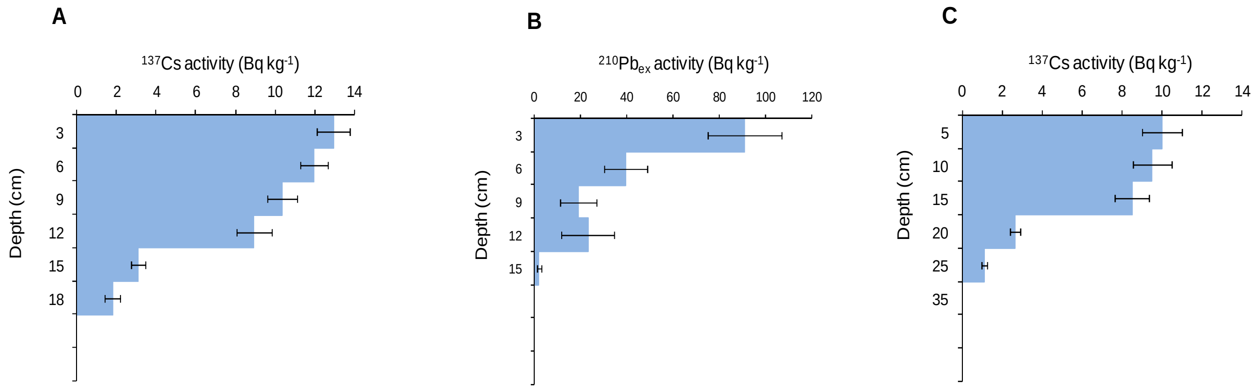

Fig.3. Depth distributions of ^{137}Cs (A) and $^{210}Pb_{ex}$ (B) in 2017 and depth distribution of ^{137}Cs (C) in 2002 within the reference site.

4.2. Vertical distributions and inventories of ^{137}Cs and $^{210}Pb_{ex}$ in the study field

For the cultivated site, concentrations of both radionuclides are almost uniform throughout the plough layer (Fig.4 D & E). The mixing effect of the cultivation process is expected to progressively homogenize radionuclide activity with depth since the initial deposition of the radionuclide at the soil surface. Indeed, the depth profile collected in 2017 shows that the homogenization of ^{137}Cs activity reaches 15 cm (Fig. 4 D) with activities at about 3–4 Bq kg^{-1} in the plough layer. A similar shape of ^{137}Cs depth distribution (Fig.4 F) in the cultivated site was obtained in 2002, but the plough layer thickness seems to be slightly lower than the one found in 2017. The same plough depth as the one found in 2017 was reported by Hassouni and Bouhlassa (2006) in a study of soil erosion based on ^{137}Cs measurements in the same watershed. Regarding the vertical distribution of $^{210}Pb_{ex,}$ the tillage depth is not very clear. (Fig. 4 E). It appears to be distributed over a deeper layer than ^{137}Cs. The incremental activities associated with this sampling point are found in the range of 16 – 17 Bq kg^{-1} in the first fifteen centimeters.

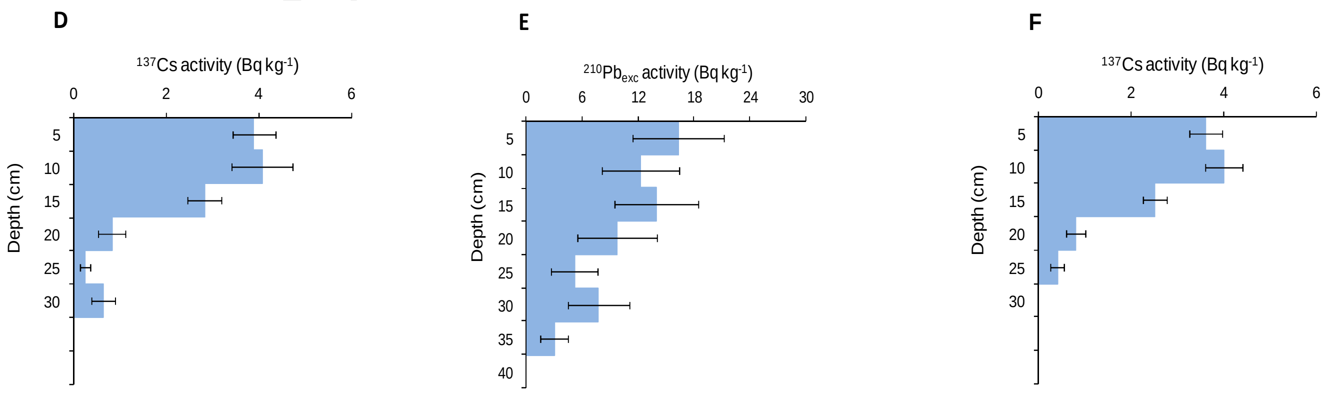

Fig.4. Depth distributions of ^{137}Cs (D) and $^{210}Pb_{ex}$ (E) in 2017 and depth distribution of ^{137}Cs (F) in 2002 within the agricultural field.

Fig.5 shows ^{137}Cs areal activities or inventories (Bq m^{-2}) measured in 2002 and decay-corrected to 2017 (Fig.5 G), versus those recorded in 2017 (Fig. 5 H), associated with the agricultural field. This provides a useful comparison to illustrate the similarities and differences in ^{137}Cs behaviour associated with the two surveys and the recent changes that have occurred during the 15 years between the two periods. Fig.5 indicates that both sets of ^{137}Cs inventories derived from the twenty samples provided by the original and the re-sampling campaigns along the four parallel transects are substantially lower than the reference inventory (Fig. 5). This shows that the site has mostly been exposed to soil erosion over the investigated periods of 1954–2002 and 1954–2017. Indeed, the previous decay-corrected inventories from 2002 to 2017 ranged from 195 to 846 Bq m^{-2} whereas the recent inventories measured in 2017 ranged from 91 to 1228 Bq m^{-2}. They were significantly lower than the reference inventories of 1520 Bq m^{-2} and 1517 Bq m^{-2} obtained in 2002 and 2017 respectively (Fig. 5). Hence, both investigations affirmed that the tendency of soil movement is eroding. Furthermore, it is noticeable that the highest ^{137}Cs concentrations that were in the downslopes of the four transects (Fig 5. G) were displaced to the middle parts (Fig 5. H). This suggests that the middle part of the field becomes more stable than the lower part. However, it does not disprove the fact that the inventories still conserve the increasing trend in the downslope boundaries (Fig 5. H).

Mean ^{137}Cs inventories and their uncertainties associated with each transect for both periods are reported in Table 2. ^{137}Cs inventories recorded in 2017 are generally lower than those previously recorded in 2002, except for transect 2. However, ^{137}Cs inventories measured in 2017 slightly exceed those obtained in 2002 once decay-corrected to 2017 (Fig. 5). Nevertheless, taking into account the uncertainties (Table. 2), the ^{137}Cs inventory values measured in 2017 appear to be close to those of 2002 after radioactive decaying. These results mean that during the period from 2002 to 2017, there was a stabilization or no significant loss of fallout of ^{137}Cs from the agricultural field for most of the transects except transect 2, where there was an increase of the ^{137}Cs inventory. This stabilization of ^{137}Cs inventories, which is observed in the middle part of the field (Fig 5.H), for most transects (Transects 1, 2 and 4) could be explained by the positive impact of recent agricultural practices consisting of more frequent fallows combined with natural vegetation and olive plantations in addition to the cultivation tradition based on legume-cereal crop rotation. Transect 2 seems to be subject to a gain in ^{137}Cs activity as a result of deposition or accumulation of soil during the last fifteen years, conducting to a significant decrease of the mean soil erosion rates between the two periods (1954-2002, 1954-2017). Overall, the obtained results show that soil erosion has been mitigated in the agricultural field during the period 2002-2017.

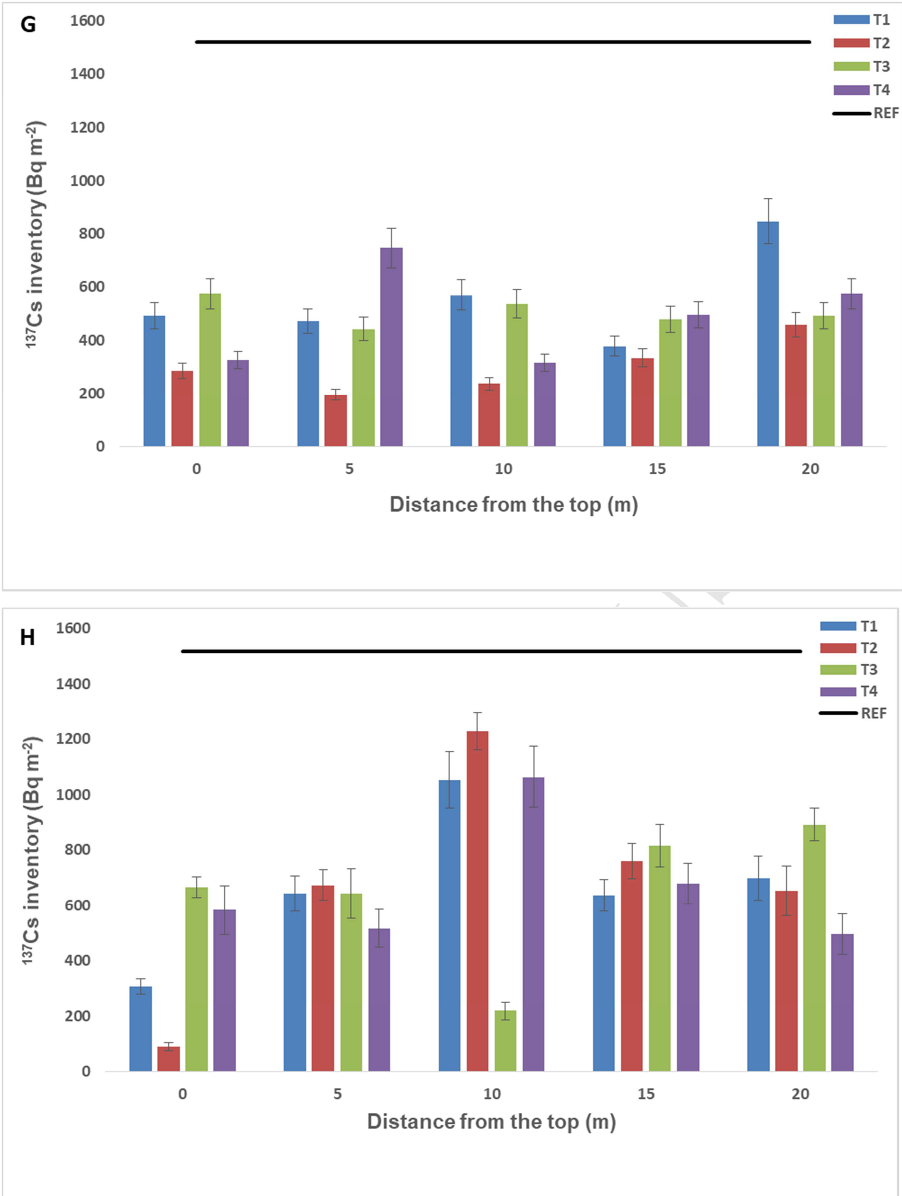

Fig.5. Decay-corrected ^{137}Cs inventories from 2002 to 2017 (G) and ^{137}Cs inventories recorded in 2017 (H) at the twenty sampling points along the four parallel transects (T1, T2, T3, T4) within the agricultural field compared with the reference inventory (REF).

Table 2. Mean ^{137}Cs and $^{210}Pb_{ex}$ inventories with uncertainties associated with the four transects.

Transect	^{137}Cs inventories recorded in 2002 (Bq m^{-2})	Decay-corrected ^{137}Cs inventories from 2002 to 2017 (Bq m^{-2})	^{137}Cs inventories recorded in 2017 (Bq m^{-2})	$^{210}Pb_{ex}$ inventories recorded in 2017 (Bq m^{-2})
Transect 1	777 ± 78	551 ± 55	668 ± 65	2290 ± 1173
Transect 2	426 ± 43	302 ± 30	681 ± 69	2620 ± 929

Transect 3	711 ± 71	504 ± 50	647 ± 65	2567 ± 974
Transect 4	693 ± 69	491 ± 49	668 ± 85	2290 ± 1119

$^{210}Pb_{ex}$ inventories were measured in 2017 as well. The values of $^{210}Pb_{ex}$ inventories within the field ranged from 464 to 5380 Bq m^{-2}, while the mean reference inventory was about 3662 ± 1404 Bq m^{-2}. Table 2 also summarizes the mean $^{210}Pb_{ex}$ activities along the four transects. These areal activities are much higher than ^{137}Cs areal activities obtained from the same sampling campaign. In contrast to ^{137}Cs, deposition is recorded within the field over the past century based on $^{210}Pb_{ex}$ technique (Fig. 6). Most of the depositional points are located in the middle part of the transects and more erosional points are observed at the upslope boundary, whereas the downslope part seems to be nearly stable. However, even if the deposition was not observed for the period of 1954-2017, using the the ^{137}Cs technique, it has to be noted that the middle part of the field (Fig.5 H) is less eroded, while more erosional points are found at the upslope boundary. However, relative uncertainties, derived from Table 2, associated with $^{210}Pb_{ex}$ activities are significantly higher, about 35-50%, than those corresponding to ^{137}Cs activities, 9-12 % (Table 2).

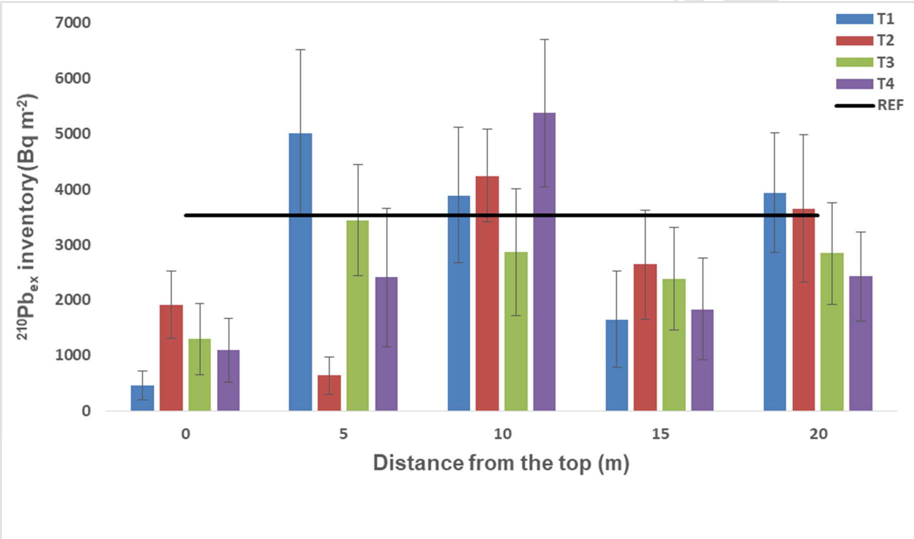

Fig.6. Comparison of the $^{210}Pb_{ex}$ inventories of the twenty samples along the four parallel transects (T1, T2, T3, T4) with the $^{210}Pb_{ex}$ reference inventory (REF).

4.3. Estimates of erosion rates basing on samples collected in 2002 and 2017 within the study site

Soil erosion or deposition rates were estimated based on ^{137}Cs and $^{210}Pb_{ex}$ measurements and using Mass Balance Model (2). The parameters of MBM2 were determined as follows:

γ= 0.5; H= 5.7 kg m^{-2} ; d_{2002}= 142 kg m^{-2} ; d_{2017}=213 kg m^{-2} ; P=1; previous ^{137}Cs A_{ref}=2142 Bq m^{-2} ; recent ^{137}Cs A_{ref}=1517 Bq m^{-2} ; $^{210}Pb_{ex}$ A_{ref} =3662 Bq m^{-2}.

By using fallout ^{137}Cs, soil erosion rates associated with the four transects were determined for both periods: 1954-2002 and 1954-2017. During the first period, the net soil erosion rates along the four transects ranged from 30.1 to 48.6 t ha^{-1} yr^{-1} (Table 3), whereas during the second period, the net soil erosion rates were found between 26.1 and 33.7 t ha^{-1} yr^{-1}, lower than the previous values (Table 3). It should be noted that net soil erorion rate (t ha^{-1} yr^{-1}) within a field represents the difference between the gross soil erosion rate (t ha^{-1} yr^{-1}) and the gross soil deprosition rate (t ha^{-1} yr^{-1}) (IAEA, 2014). The results show that the net

soil erosion rate associated with the whole field, taking into account the values of all transects, has considerably decreased from 36.1 ± 8.5 t ha^{-1} yr^{-1} in 2002 to 29.0 ± 3.4 t ha^{-1} yr^{-1} in 2017 (Table 3). This significant decrease that occurred was probably due to sustainable agricultural practices, consisting of more frequent fallows combined with natural vegetation and olive plantations in addition to crop rotation. Adopting appropriate agricultural practices has been recommended by the authorities, in order to reduce soil erosion in the watershed and sedimentation in the downstream water reservoir (Nakhla dam) and to mitigate the impact of climate change on land degradation. These practices have become habits of the population in the Rif Mountains for a long time. At the watershed scale, the impact of the soil management strategy can also be evaluated by measuring the amounts of sediment deposited at the Nakhla dam. Indeed, the availability of such measurements, albeit discontinuous, made it possible to follow the evolution of sedimentation in Nakhla dam throughout the years. In this regard, according to data provided by the "Hydraulic Basin Agency of Loukkos" in the north of Morocco, the annual amount of sediment delivered to Nakhla dam increased from 0.11 Mm^3 yr^{-1} in 1979 to 0.41 Mm^3 yr^{-1} in 1996 and was reduced to 0.05 Mm^3 yr^{-1} in 2004. The progressive decreasing trend in sediment yield is in agreement with the obtained results, confirming the potential of using ^{137}Cs measurements for re-sampling investigations.

A study conducted by Fornes et al. (2005) in a cultivated field in southern Lowa, USA, based on the same approach for 1954-1974 and 1954-1998, found that reduced soil loss and greater deposition were attributed to the introduction of grass buffer strips and conservation tillage. A study carried out by Loughran and Balog (2006) highlighted the progressive reduction in soil erosion as a result of the incorporation of subsoil into the plough layer, and the cessation of clean till cultivation. The study was carried out within a vineyard in Australia by measuring ^{137}Cs in samples collected in 1984-1985 and others collected in 2004 following the same scheme but in different locations. In the study reported by Porto et al. (2014), both estimates of mean annual soil loss for the periods 1954-1998 and 1999-2013 derived using ^{137}Cs measurements with the re-sampling technique and the measurements of mean annual sediment yield, provided similar evidence of a lack of change in soil redistribution.

According to Porto et al. (2014), the period between the two sampling campaigns should be long enough to converge to the time-integrated by the employed fallout radionuclide and to ensure that the comparison generates statistically significant results. In the case of this study, fifteen years were enough to translate the evolution of the vulnerability of soil to water erosion within the study area and reveal the beneficial impact of the mentioned measures on soil stabilization.

Table 3 provides the possibility of a direct comparison of erosion rates obtained for individual sampling points along the four transects for the two periods. Generally, there are two types of comparison in the investigations related to re-sampling, either compare point by point or look at the general tendency of soil movement within the transects and the field. Obviously, all the sampling points are characterized by net soil loss within the two periods, but the severity of soil erosion has been reduced. The estimates of mean annual soil redistribution rates at the sampling points within the field ranged from 16.4 to 60.8 t ha^{-1} yr^{-1} for the period 1954-2002 and from 6.2 to 91.6 t ha^{-1} yr^{-1} for the period 1954-2017. The estimates indicate that 70% of the values provided by the samples collected in 2017 are lower than those provided by samples collected in 2002. At the scale of the whole field, transect 2 had conserved its trend of recording the highest erosion rates compared with other transects. The relative standard deviations associated with the two values of soil erosion rates in the whole field for both periods, based on the values obtained for the four transects, are about 23% and 13% for previous and recent periods respectively. The fact that the recent rates at the whole transects converge more means that the recent soil redistribution becomes more homogeneous within the field than before. Furthermore, in accordance with the inventories trend (Fig.5 H), the middle part of the field has become less eroded, whereas the upslope positions were more eroded in the two periods (Table 3). The contrasts between

the two distributions are attributed to the re-sampling errors, to the precision of the gamma spectrometry of the two sets of measurements to obtain ^{137}Cs inventories for the individual sampling points and to the uncertainty associated with the conversion model and its parameters (Porto et al., 2014).

Table 3. Soil redistribution rates provided by the twenty points along the four parallel transects collected in 2002 and 2017 based on ^{137}Cs measurements and MBM2 (period ~ over 50-60 years).
$^{(*)}$ Standard deviation

Transect/ field	Soil redistribution rates (t ha^{-1} yr^{-1}) in 2002						Soil redistribution rates (t ha^{-1} yr^{-1}) in 2017					
	Erosion rates along the transects					Net erosion rates	Erosion rates along the transects					Net erosion rates
	0m	5m	10m	15m	20m	Whole transect	0m	5m	10m	15m	20m	Whole transect
T1	32.4	33.6	28.0	40.3	16.4	30.1	49.5	25.9	10.9	26.3	23.3	27.2
T2	48.8	60.8	54.7	44.1	34.5	48.6	91.6	24.5	6.2	20.8	25.4	33.7
T3	27.7	35.5	29.8	33.2	32.4	31.7	24.8	25.9	60.7	18.6	15.9	29.2
T4	44.8	20.0	45.7	32.2	27.7	34.1	28.9	32.7	10.5	24.3	34.0	26.1
Whole field	36.1 ± 8.5$^{(*)}$						29.0 ± 3.4$^{(*)}$					

It was important to consider the estimates of soil erosion based on $^{210}Pb_{ex}$ since the integrated time window permits to quantify soil erosion for a longer period (~100 years). The value obtained by $^{210}Pb_{ex}$ translates long-term watershed response to agro-climatic conditions. Despite its advantages, studies reporting the use of $^{210}Pb_{ex}$ for soil erosion are still scarce in Morocco (Benmansour et al., 2011, 2013; Ibrahimi, 2005).

For the present investigation, erosion rates ranged from 0.1 to 203.9 t ha^{-1} yr^{-1}, while deposition rates ranged from 12.6 to 84.1 t ha^{-1} yr^{-1} (Table 4). By analogy with ^{137}Cs results, the middle parts of the transects are more stable while the upslope parts are more eroded. In spite of the high uncertainties associated with $^{210}Pb_{ex}$ measurements and more dispersion of soil erosion rate values (Table 4) compared to those obtained by ^{137}Cs technique, the net soil erosion rates obtained along the four transects are close to each other. Indeed, the net soil erosion rates obtained along the four transects ranged from 22.9 to 34.5 t ha^{-1} yr^{1}. The rate corresponding to the whole field is estimated at 27.1 ± 5.4 t ha^{-1} yr^{-1} over a period of 100 years (Table 4).

Considering that there is no significant change in agricultural practices in the watershed only after the end of the nineties, the lower soil erosion rate of about 27 t ha^{-1} yr^{-1} estimated over 100 years (1917-2017) using $^{210}Pb_{ex}$ compared to the rate of 29.0 t ha^{-1} yr^{-1} provided by ^{137}Cs technique, associated with shorter period (1954-2017), could reflect the impact of climate change on the soil erosion rate between the two periods. However, taking into account the high uncertainties on $^{210}Pb_{ex}$ measurements and the lack of complete data on climatic conditions, we can conclude that there is no observable change in soil erosion rate due to climate change impact over time.

Table 4. Soil redistribution rates provided by the twenty points along the four parallel transects collected in 2017 based on $^{210}Pb_{ex}$ measurements and MBM (period: over 100 years).

$^{(*)}$: Deposition in bold

Transect/ field	Soil redistribution rates (t ha^{-1} yr^{-1}) in 2017					
	Erosion/**Deposition**$^{(*)}$ rates along the transects					Net erosion rates
	0m	5m	10m	15m	20m	Whole transect
T1	203.9	**84.1**	**14.1**	45.4	**12.6**	27.7
T2	35.8	141.1	**21.1**	16.8	0.1	34.5
T3	63.6	3.1	12.4	22.5	12.9	22.9
T4	78.0	22.0	**44.1**	38.4	21.6	23.2
Whole field	27.1± 5.4					

5. Conclusion

The study reported in this paper has attempted to assess the potential of combining ^{137}Cs measurements and the re-sampling approach with $^{210}Pb_{ex}$ measurements to establish recent changes in soil redistribution rates within a watershed in the northwest area of Morocco. Indeed, it proved that this approach meets the requirement of a new scientific alternative to retrospectively assess changes in the pattern of soil movements. The findings indicated that there is a decrease in soil loss in the investigated field due to suitable soil management strategies and sustainable agricultural practices. A close correspondence was found between the decrease in the mean annual soil loss from the agricultural field and the recorded sediment yield at the watershed scale, which validates the use of ^{137}Cs measurements coupled with the re-sampling approach. It is true that the implemented measures were enough to reduce the magnitude of soil erosion in the area. However, innovation in the optimization of soil conservation strategies is always requested to deal with the updates in natural and anthropic constraints and ensure sustainable agricultural development in the Rif Mountains.

This study represents the first attempt to apply ^{137}Cs re-sampling combined with $^{210}Pb_{ex}$ techniques in Northwest Africa to detect the impact of land use on soil erosion under Mediterranean agro-climatic conditions. The work will be pursued for a better understanding of the impact of agricultural practices and global change on soil erosion in Northern Morocco.

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Highlights

- Caesium-137 technique with re-sampling approach were successfully used to study recent changes in soil redistribution rates.
- Lead-210 in excess allowed to assess soil erosion rates over the last century in the study field.
- Sustainable agricultural practices and suitable erosion control strategy have reduced the magnitude of soil erosion in the study field.
- The decreasing trend in sediment yield was in agreement with the obtained results using Caesium-137 re-sampling approach.
- There is no observable change in soil erosion rate due to climate change impact over time.